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INITIAL INVESTIGATIONS OF THE PRODUCTIVE PERCHED AQUIFERS ON THE VOLCANIC ISLAND OF MONTSERRAT

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ABSTRACT

An understanding of hydrological processes on volcanic islands is vital for both resource and hazard management. The hydrological system can modify the volcanic hazard and react to volcanic perturbations. Understanding this interaction is essential for the development of a truly multi-parameter hazard-monitoring dataset. The Caribbean island of Montserrat provides a unique environment to study such interactions, since it has both active volcanic and hydrological systems. We aim to gain a more complete understanding of the fundamental hydrology in active volcanic island arc settings by using TOUGH2 models to explore the natural productive springs on the flanks of the extinct volcanic center, adjacent to the active Soufrière Hills Volcano.

INTRODUCTION

A quantitative understanding of hydrology is important for resource management in all island settings. On volcanic islands, such an understanding is also crucial for assessing the interaction between groundwater and volcanic processes. For example, pressurization of pore waters due to magmatic heating can lower effective stresses and cause catastrophic flank collapse (Reid, 2004). The transfer of magmatic heat to circulating groundwater can generate explosive phreatic eruptions (Germanovich and Lowell, 1995) and direct interaction between groundwater and rising magma can produce violent phreatomagmatic explosions. Such events have been observed to precede the onset of major eruptive phases (e.g., the 1995 Soufrière Hills Volcano eruption (Young et al., 1998)) and are also capable of generating large volumes of ash, which can significantly extend the spatial extent of disruption associated with even a minor eruption (e.g. Eyjafjallajökull 2010 (Sigmundsson et al., 2010)).

Hydrological and volcanic interactions play a significant role in the development of valuable mineral deposits, as meteoric and magmatic fluids interact and circulate, driven by large geothermal gradients (Hedenquist and Lowenstern, 1994). The presence of high geothermal gradients and hydrological aquifers also make volcanic islands favorable locations for geothermal energy development (e.g., Nisyros, Greece (Koutroupis, 1992) and Basse-Terre, Guadeloupe (Brombach et al., 2000)). Geothermal energy generation is currently being actively investigated on the volcanic island of Montserrat (Younger, 2010).

Hydrological systems have also been observed to respond to volcanic perturbations (Hurwitz and Johnston, 2003). It is therefore possible that the hydrological system may hold valuable information about the state of a restless volcano prior to eruption. Hautmann et al. (2010) proposed that groundwater migration, in response to changes in volcanic activity, may be responsible for residual gravity anomalies recorded on Montserrat between 2006 and 2008. The potential for groundwater fluxing to represent an eruption precursor and to disrupt the geophysical monitoring of an active volcano demonstrates that understanding the hydrological system in volcanic settings is essential for the development of a truly multi-parameter hazard-monitoring dataset.

The Caribbean island of Montserrat, in the Lesser Antilles volcanic island arc (Figure 1). hosts a number of productive perched springs as well as confined aquifers. The presence of both active volcanic and hydrological systems, as well as the progressive ages and maturity of the geology, means that Montserrat provides a unique environment to study interactions between hydrological and volcanic systems.

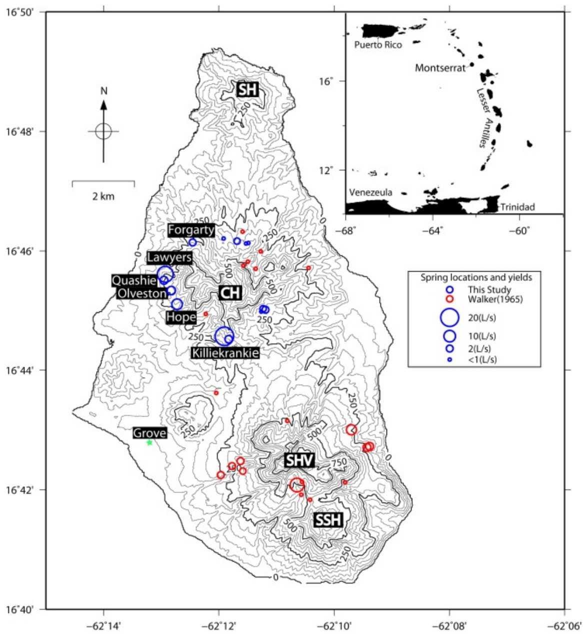

Figure 1. The location of Montserrat's springs and the island's context in the Lesser Antilles. The major springs and the four major volcanic centers are labeled: Silver Hills (SH), Centre Hills (CH), Soufrière Hills Volcano (SHV) and South Soufrière Hills (SSH). Grove rain gauge is also displayed

In this paper, we present the preliminary results from TOUGH2 simulations (Pruess, 1991) that investigate a conceptual understanding of the fundamental hydrogeology of the extinct Centre Hills (CH) complex (0.5–1 Ma), by exploring seasonal spring discharge fluctuations. Ultimately, TOUGH2 models will be developed to explore fluctuating spring production behavior and temperature anomalies that are potentially associated with volcanic activity.

MONTSERRAT

Montserrat is composed of four major volcanic centers. The oldest center, Silver Hills (SH) at the northern tip of the island, is estimated to have been active between 2.6 and 1.2 Ma before present (Harford et al., 2002). Activity on the currently erupting Soufrière Hills Volcano (SHV), in the south of the island, dates back to 170 Ka. The central portion of the island is dominated by the dome complex and eruptive deposits of the extinct Centre Hills volcano (CH), active from 1 to 0.5 Ma (Harford et al., 2002). With the exception of the slightly anomalous South Soufrière Hills (SSH), which erupted between two major eruptive phases of SHV, the style of eruption among the island's volcanoes is thought to be very similar. This apparent consistency in eruptive style means that the island's centers provide a unique insight into the evolution of a system, from the building of a complex volcanic edifice (SHV), to the eventual erosion back to the central core and most proximal deposits of an extinct volcano (SH).

After an initial period of phreatic explosions, in 1995, the ongoing eruption at SHV has been characterized by periods of dome growth and subsequent collapse. The domes grow by extrusion of highly viscous andesitic spines that break off to form blocky and often unstable, talus slopes (Watts et al., 2002). As the domes grow, they can become gravitationally unstable or undermined by slope weakening associated with hydrothermal activity. Dome collapses generate volcaniclastic deposits, including clay-rich debris avalanches, pyroclastic flows, surges, and lahars. Collapse events have also been triggered by violent vulcanian explosions that produce pumice-rich flows, surges, and lahars, as well as significant volumes of ash. Dome collapse events have also been correlated with periods of intense rainfall (Matthews et al., 2002; Barclay et al., 2006).

Montserrat has a subtropical maritime climate and experiences both local, convective storms and heavy rainfall associated with larger tropical weather systems. While rainfall occurs throughout the year, there is a clear seasonality (Figure 2). The wet season extends from July to November, decreasing through December and January into a dry season, which begins in February and ends abruptly in May.

Throughout the year, brief (minute–hour) but intense convective storms provide the majority of the baseline precipitation, while large tropical depressions and hurricanes contribute much of the wet season precipitation. For example, the passing of Hurricane Earl in August 2010, 150 km off the east coast of Montserrat, delivered almost 10% of the recorded annual rainfall in just a few hours. There is also significant spatial rainfall variation, with strong orographic control; the peaks of CH and SHV (~750 and 900 m elevation respectively) receive ~2500 mm/yr, compared with ~1200 mm/yr and ~ 1800 mm/yr closer to sea level on the windward (east) and leeward coasts.

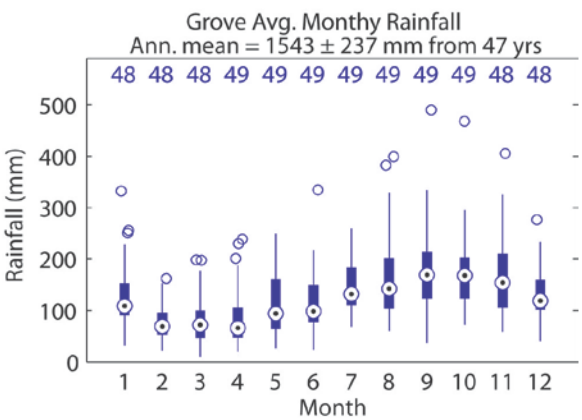

Figure 2. Median monthly rainfall with 25th and 75th percentiles and data limits from Grove rain gauge between 1905 and 1965.The number of years contributing to the medium for each month is give at the top of the plot. Data provided by Montserrat Utilities Ltd (MUL).

Despite relatively high precipitation, there is very little surface water on the island. The steep flanks are drained by a radial system of deeply incised valleys, known locally as ghauts. These ghauts are generally ephemeral, only discharging to the sea during intense or prolonged rainfall events. Whereas springs on SHV have been buried by the ongoing eruption, on CH the loosing streams are sourced from perched springs at elevations between 250 and 450 m (Figure 3). There are a few broader drainage channels, such as the Belham and Farm River valleys, between CH and SHV, which receive contributions from a number of ghauts, as well as inundation with lahars from SHV. The channels in these broader valleys are also ephemeral, with rapid infiltration into the reworked channel and lahar deposits.

Water supply for the population of Montserrat (~5,000 in 2011) is entirely reliant on spring systems on the slopes of CH. Six of the first- and second-order springs (labeled in Figure 1) are trapped for supply, providing, on average, 35 L/s of potable water.

Seasonal variations in rainfall are reflected in spring discharge fluctuations with lag times on the order of 3 to 9 months. Chemical analysis shows no obvious volcanic signature in CH spring waters (Chiodini et al., 1996; Jones et al., 2010). However, our data shows spring temperature variations, suggesting that the Centre Hill hydrological system may not be totally decoupled from the volcanic system to the south (Figure 3).

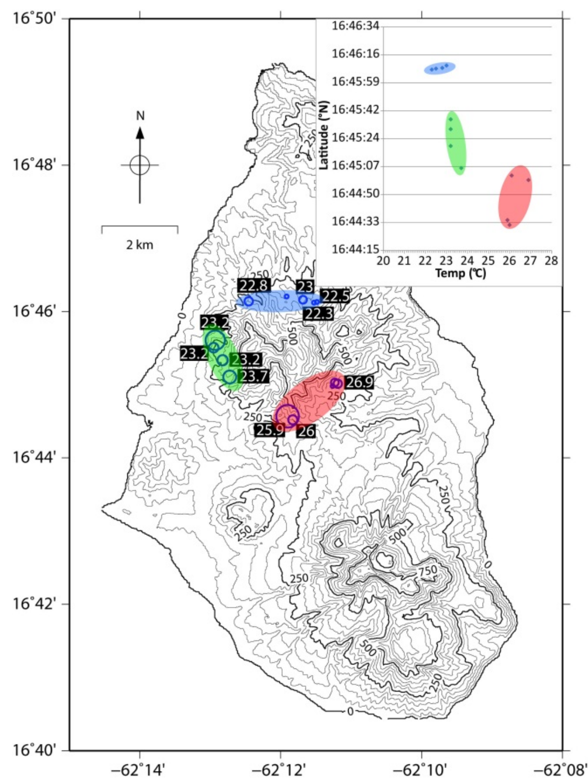

Figure 3. Temperature of the CH springs in °C. Springs on the southern flank, closest to the active SHV, are noticeably warmer than those to the west and north.

The productivity of springs on Centre Hills and pre-eruptions on SHV have been documented to fluctuate “appreciably” in response to seismic and volcanic unrest (Ramdin and George, 1995). However, this is difficult to validate, since spring yield data was not recorded in the aftermath of Hurricane Hugo in 1989 or for over five years after the onset of Phase 1 of volcanic activity in 1995 (Phase 1) (Figure 4). Data are available for the period between 1991 and 1995, when precursor seismicity was intensifying, and during dome growth phases 2–5 (2001–present). However, the poor temporal resolution of the spring discharge record (monthly) and the complex interplay between recharge and spring discharge obscures any definitive relationship with volcanic activity

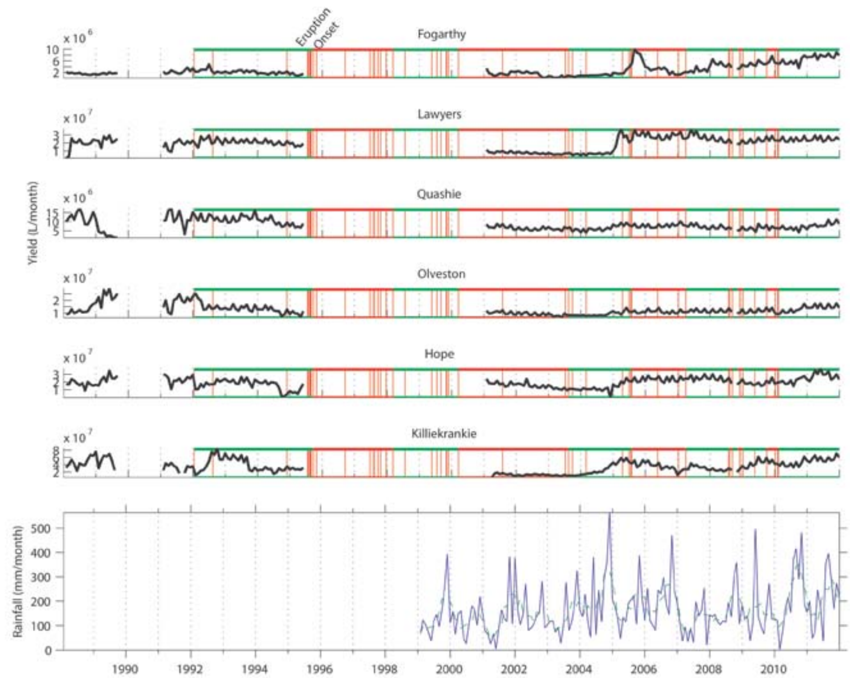

Figure 4. Monthly spring discharge data for the six CH springs used for supply. The onset of the eruption in July 1995 is marked. Red horizontal bars show periods of lava extrusion; green represents pauses where no extrusion occurs. Vertical red lines are timings of distinct events, including seismic swarms, explosions (phreatic and vulcanian) and dome collapse events. Available monthly rainfall data is shown below for a rain gauge at Hope (see Figure 1). Gaps in the spring data are due to disruption caused by Hurricane Hugo in 1989 and the onset of eruption in 1995. Data provided by MUL.

In addition to multiple perched aquifers on the flanks of the Montserratian volcanoes, there are a number of water-bearing aquifers in the more distal, reworked deposits of the major drainage valleys of Belham and Farm, in the west and east respectively, and Carr's and Little Bay, in the north. Three wells in the Belham Valley tap a confined aquifer in reworked gravels and alluvial deposits 20 m below mean sea level. The water level in the wells rose between 2005 and 2006 (Figure 5), a period that included a switch from pause to extrusion at the end of July 2006, and a number of explosion events. The water level in all three wells dropped abruptly a week after a major dome collapse in May 2006, before continuing its general upward trend. In 2011, well MBV2 became flowing artesian; in November 2011 it was flowing at a rate of 3.2 L/s.

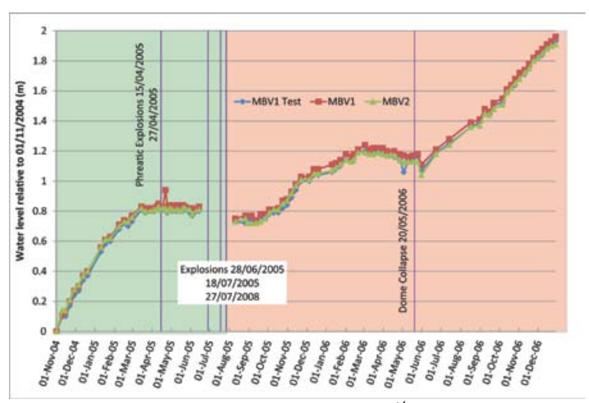

Figure 5. Water level relative to 1st November 2004 in artesian wells in the Belham Valley. Green zone denotes period of no growth; red represents period when lava extrusion is taking place. Vertical purple lines highlight dates of explosive activity or collapse events. Data provided by MUL

THE CONCEPTUAL MODEL

Both the presence of perched springs on the flanks of the younger volcanic centers of Montserrat, and the confined aquifers within the larger drainage valleys which extend below sea level, suggest that substantial low-permeability units are present among the generally high permeability volcaniclastic stratigraphy. The work here concentrates on exploring the nature of these spring systems.

There exist a number of conceptual models that may be applicable to the spring systems on Montserrat. Bramble and Barragne-Bigot (1988) envisaged aquifers of "faulted and jointed volcanic cores" overlying aquicludes of "clayey and unsorted pyroclastic deposits". In contrast, Davies and Peart (2003) proposed spring zones occurring at "the junction between permeable coarse-grained pyroclastic deposits that surround the central volcanic rock core and the impermeable fine-grained pyroclastic flow deposits". Elsewhere in the Lesser Antilles, clay-rich, bulge landslide deposits are postulated to be capable of ponding groundwater on the flanks of Mount Pelée, Martinique (Zlotnicki et al., 1998). Finally, based on observations at nearby Basse-Terre, Guadeloupe, Charlier et al. (2011) indicate that weathered volcanic breccia forms a lower permeability zone, underlying relatively permeable pyroclastic and lava formations at spring sites.

MODELING

This study uses TOUGH2 to explore alternative conceptual models for CH springs. Here, we present results from initial simulations, based on the observations of Charlier et al. (2011) from Basse-Terre. We simulate a perched aquifer developed on a low-permeability layer in an otherwise permeable, but unsaturated, subsurface, and evaluate the fluid flux from a spring draining this perched aquifer.

Geometry

The model space represents a 2D linear cross section through CH with representative surface topography. The model extends from -250 to 750 m in z and 0 to 4000 m in x. The width in y is defined as one unit cell thick. The model is discretized in into 300 regular 13.3 m wide columns (Figure 6). Porosity and isotropic permeability are specified as 35% and 1e-12 m^2 throughout the model, with the exception of a 10 m thick layer between 225 and 235 m elevation, which represents the aquiclude. Porosity and isotropic permeability of the aquiclude is 10% 1e-16 m^2, respectively. Cell thickness is defined as 25 m throughout the model, except in the aquiclude and the lower 120 m of the layer above, where the cell thickness is refined to 2 m and 5 m respectively. The top and bottom layers of cells in the model are set at infinite volume, to allow open boundaries for liquid and gas flow.

Initial conditions define the top of the saturated zone at z=0 m. Relative permeability and capillary pressure are defined by the van Genuchten-Mualem model and van Genuchten function, respectively (van Genuchten, 1980) using parameters from values for volcanic sands given by Fischer and Celia (1999) (Table 1).

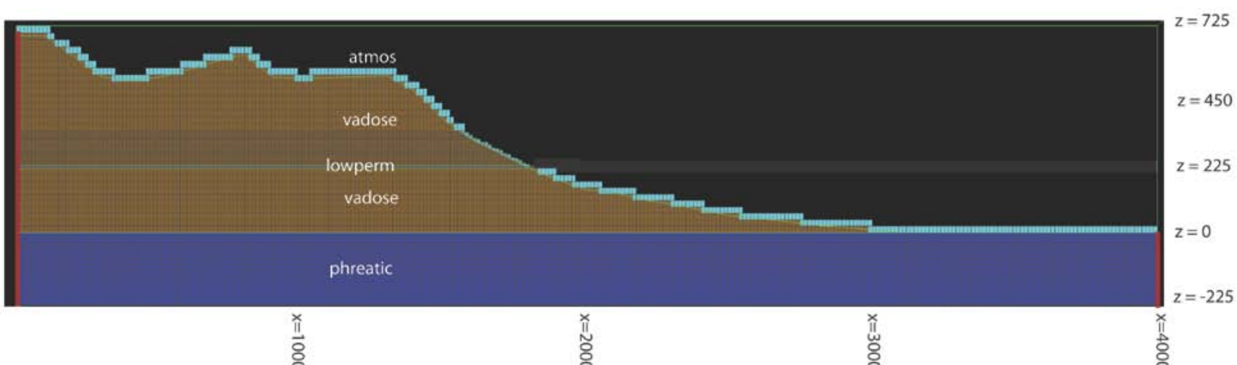

Figure 6. Geometrical setup of model. X limit boundaries are closed to flow (red bars).Top and bottom cell layers have infinite volume and are open to flow.

Table 1. Relative permeability and capillary pressure parameters used for unsaturated zone models. Based on values for volcanic sands from Fischer and Celia (1999). S_r^l is the irreducible liquid saturation; S_s^l is the maximum liquid saturation; S_r^g is the irreducible gas saturation and m and α are the van Genuchten parameters.

	Relative Permeability.	Capillary Pressure
Function	van Genuchten-Mualem	van Genuchten
m	0.85	0.85
S_r^l	0.16	0.16
S_s^l	1.0	1.0
S_r^g	0.0	
α (m^{-1})		45

The models are run in two stages. For Stage 1, the unsaturated zone is initially set to uniform gas saturation (S_g) of 0.84 ($S_s^l - S_r^l$) and atmospheric pressure. Initial conditions for the saturated zone are $S_g = 0$ with a hydrostatic pressure gradient. The model is run to equilibrium with a constant input flux defined in the top cells of the vadose zone. The input is equivalent to 2.1 m/yr, which is equal to the mean annual rainfall recorded at the Hope rain gauge on the western flanks of CH (2006 and 2011). During Stage 1, a perched aquifer develops above the low-permeability layer. Discharge from the cells at the base of this aquifer increases rapidly as the perched aquifer develops, reaching steady state after some 50 years (Figure 7). At this time, ~18% of recharge water percolates through the perched aquifer.

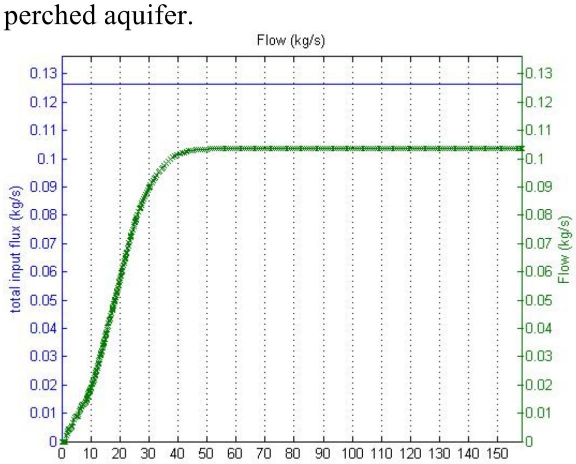

Figure 7. Recharge flux and associated modeled spring discharge (kg/s) for Stage 1 run.

Stage 2 tests the discharge response of the modeled spring to a weekly fluctuating recharge input. Initial conditions for Stage 2 are prescribed by the final conditions of Stage 1 (Figure 8). Recharge rate now varies through time for 6 years, before returning to the mean value used in Stage 1 for a further 6 years. The variable recharge rate is based on the recorded weekly rainfall time series (2006–2011 incl.) at Hope.

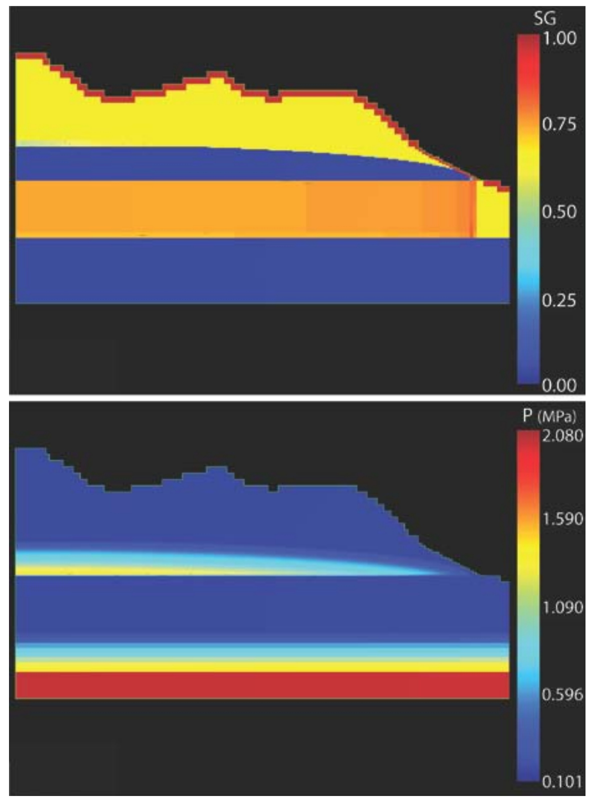

Figure 8. Gas saturation (top) and pressure (bottom) conditions for Stage 2.

INITIAL RESULTS

Initial simulation results from Stage 2 show a very rapid response of the modeled spring discharge to fluctuations in recharge (Figure 9). This does not reflect known temporal variations in spring discharge, where seasonal lag is observed to be on the order of 3 to 9 months. The region immediately above the spring sites on CH is generally characterized by very steep slopes. On such steep slopes, runoff often dominates over infiltration and groundwater recharge is limited. Removing recharge from cells that define the slope in the 120 m above the aquiclude has a dramatic effect on the modeled discharge response (Figure 10).

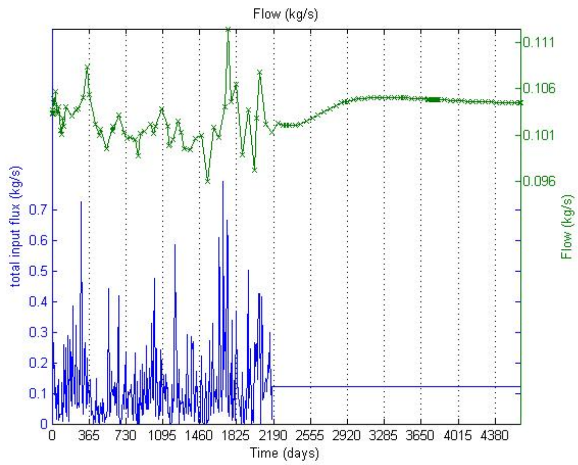

Figure 9. Modeled spring response to fluctuating recharge event.

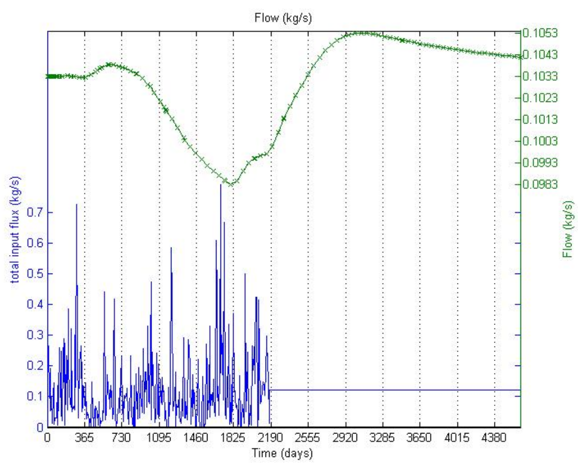

Figure 10. Modeled spring response to fluctuating recharge event, with recharge cells restricted.

DISCUSSION AND FUTURE WORK

The results demonstrate the sensitivity of the models to defined recharge locations. Modifying the specified recharge input with respect to slope angle should account for runoff dominating on steep slopes. Evapotranspiration (ET) would lower recharge further, suggesting that the input fluxes used in these simulations may be excessive. ET of 30% may be typical for the Lesser Antilles (Rad et al., 2007). Incorporation of ET and runoff could reduce net recharge significantly; however, markedly higher rainfall in the recharge area, above the springs, compared with levels recorded at the lower elevation rain gauge on the western flank, could offset this effect.

Further refinement of the method presented here is required, to allow a more quantitative investigation of seasonal fluctuations in spring discharge. Further TOUGH2 simulations can then explore the conceptual models and ultimately help provide an insight into hydrological interactions on active volcanic islands.

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